

# A perspective on Quantum Gravity Phenomenology<sup>1</sup>

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## ABSTRACT

I give a brief overview of some Quantum-Gravity-Phenomenology research lines, focusing on studies of cosmic rays and gamma-ray bursts that concern the fate of Lorentz symmetry in quantum spacetime. I also stress that the most valuable phenomenological analyses should not mix too many conjectured new features of quantum spacetime, and from this perspective it appears that it should be difficult to obtain reliable guidance on the quantum-gravity problem from the analysis of synchrotron radiation from the Crab nebula and from the analysis of phase coherence of light from extragalactic sources. Forthcoming observatories of ultra-high-energy neutrinos should provide several opportunities for clean tests of some simple hypothesis for the short-distance structure of spacetime. In particular, these neutrino studies, and some related cosmic-ray studies, should provide access to the regime  $E > \sqrt{mE_p}$ .

## 1 Quantum Gravity Phenomenology

Quantum-gravity research used to be completely detached from experiments. The horrifying smallness of the expected quantum-gravity effects, due to the overall suppression by powers of the ratio of the Planck length ( $L_p \sim 10^{-35}m$ ) versus the characteristic wavelength of the particles involved in the process, had led to the conviction that experiments could never possibly help. But recently there has been a sharp change in the attitude of a significant fraction of the quantum-gravity community. This is reflected also by the tone of recent quantum-gravity reviews (see, *e.g.*, Refs. [1, 2, 3, 4]) as compared to the tone of quantum-gravity reviews published up to the mid 1990s (see, *e.g.*, Ref. [5, 6]).

The fact that the smallness of an effect does not necessarily imply that it cannot be studied experimentally is not actually a new idea, and indeed it finds support in several examples in physics. Even remaining in the context of fundamental physics there is the noteworthy example of studies of the prediction of proton decay within certain grandunified theories of particle physics. The predicted proton-decay probability is really small, suppressed by the fourth power of the ratio between the mass of the proton and the grandunification scale  $[m_{proton}/E_{gut}]^4 \sim 10^{-64}$ , but in spite of this truly horrifying suppression, with a simple idea we have managed to acquire an excellent sensitivity to the new effect. The proton lifetime

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<sup>1</sup>These notes provided the basis for the “summary talk” which I gave as chairman of the QG1 session (“Quantum Gravity Phenomenology”) at the “10th Marcel Grossmann Meeting on General Relativity” (Rio de Janeiro, July 20-26, 2003).

predicted by grandunified theories is of order  $10^{39}$ s and “quite a few” generations of physicists should invest their entire lifetimes staring at a single proton before its decay, but by managing to keep under observation a large number of protons our sensitivity to proton decay is dramatically increased.

We should therefore focus our attention[7] on experiments which have something to do with spacetime and such that there is an ordinary-physics dimensionless quantity large enough that it could amplify the extremely small effects we are hoping to discover. Over these past few years several new ideas for tests of Planck-scale effects have appeared at an increasingly fast pace, with a growing number of research groups joining the quantum-gravity-phenomenology effort.

Among the quantum-gravity-phenomenology research lines the one which has been so far most extensively developed concerns the investigation of the fate of Lorentz symmetry in quantum gravity. The relevant proposals of Lorentz-symmetry tests focus primarily on the implications of Planck-scale effects for the analysis of gamma-ray bursts[8, 9], the possible role of the Planck scale in the determination of the energy-momentum-conservation threshold conditions for certain particle-physics reaction processes[10, 11, 12, 13, 14, 15], and the possible role of the Planck scale in the evaluation of particle-decay amplitudes[16, 17].

Another key area of interest for quantum-gravity phenomenology is the one of interferometry. Possible signatures of Planck-scale physics have been considered for matter interferometers[18], for large “free-mirror” laser-light interferometers[19, 20], and for small-size laser-light interferometers whose mirrors are rigidly connected[21]. Moreover, there is a long-term research programme which focuses on possible Planck-scale-induced departures from CPT symmetry[22, 23, 24, 25, 26]. And together with these most developed quantum-gravity-phenomenology research lines several other proposals are being considered by small networks of research groups.

Rather than attempting a comprehensive review, in Section 2 I will use the example of certain tests of Lorentz symmetry to illustrate the general structure of a quantum-gravity-phenomenology research line. The discussion of gamma-ray bursts and ultra-high-energy cosmic rays that I present in Section 2 focuses on finding a direct link between one or two simple hypotheses about new properties of quantum spacetime and certain characteristic new effects. I will argue that this conservative strategy, in which the analysis does not mix too many simultaneous assumptions about the structure of spacetime at the Planck scale, can provide valuable insight on the quantum-gravity problem. In Section 3 I consider certain types of observations which represent tempting opportunities to speculate about possible implications of quantum properties of spacetime, but require us to combine several assumptions about the structure of spacetime at the Planck scale, and I argue that in these cases it might be hard to obtain reliable guidance on the quantum-gravity problem. In the closing section (Section 4) I comment on forthcoming UHE (ultra-high-energy) neutrino observatories, as one of our best chances, for the near future, of enriching significantly the type of data used in Quantum Gravity Phenomenology. And I will stress that the relevant UHE neutrinos, just like the UHE cosmic rays considered in Section 2, can give us access to a “Planck-scale ultrarelativistic regime”, in which the ratio  $E/m$  (energy versus mass of the particle) is larger than the ratio  $E_p/E$ , where  $E_p$  is the Planck energy scale ( $E_p \equiv 1/L_p \sim 10^{28} \text{eV}$ ).

## 2 The fate of Lorentz symmetry in quantum spacetime

Models based on an approximate Lorentz symmetry, with Planck-scale-dependent departures from exact Lorentz symmetry, have been recently considered in most quantum-gravity research lines, including models based on “spacetime foam” pictures[8, 27], “loop quantum gravity” models[28], certain “string theory” scenarios[29, 30], and “noncommutative geometry” [29, 31, 32].

The most studied characterization of these Planck-scale departures from Lorentz symmetry assumes that the energy/momentum dispersion relations for fundamental particles<sup>2</sup> should be modified

$$0 = f(E, \vec{p}^2, m; E_p) \simeq E^2 - \vec{p}^2 - m^2 - \eta \frac{E^n}{E_p^n} \vec{p}^2, \quad (1)$$

where the power  $n$  parametrizes one of the possible differences between alternative quantum pictures of spacetime (with the cases  $n = 1$  and  $n = 2$  usually favoured in the literature), and essentially  $\eta$  parametrizes the precise value of the scale of departures from Lorentz symmetry, which may of course be somewhat different from the Planck scale (but on the other hand one does expect, in order to work within the quantum-gravity premises of these analyses, that roughly  $\eta \sim 1$ ).

The fact that the literature has focused primarily on this parametrization of the dispersion relation is mostly due to its simplicity, which makes it a natural first step in a phenomenology of Planck-scale departures from Lorentz symmetry. However, this scenario is also more or less directly connected with various quantum-gravity proposals. In Loop Quantum Gravity preliminary results[28, 33] provide support for the dispersion relation (1). In some rather popular noncommutative spacetimes[34] one also finds evidence in favour of (1). In String Theory it appears that the modification of the dispersion relation is not automatic but emerges in presence of certain natural background fields[29, 30], and for some background configurations a dispersion relation of the type (1) is encountered[30]. The role that phenomenological studies of (1) could have in the overall development of quantum-gravity research has been stressed in the most recent reviews by experts of the field (see, *e.g.*, Refs. [1, 3, 4]).

### 2.1 Gamma-ray bursts

In principle one could test (1) by making simultaneous measurements of energy and (space-)momentum. This turns out to be rather unpractical, at least when one is aiming for the needed Planck-scale sensitivity. It is therefore generally assumed that (1) should be tested in combination with some other key kinematic property. Perhaps the most natural proposal is to study (1) with the additional assumption that the velocity  $v$  of the particle should be

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<sup>2</sup>For composites of several fundamental particles the dispersion relation could take a very different form. In particular, if the momentum of the composite is obtained by a simple sum of the momenta of the composing particles, then the energy-momentum of a composite formed by  $N$  identical fundamental particles all carrying roughly the same energy-momentum is governed by the dispersion relation  $E_{TOT}^2 \simeq N^2 E^2 = N^2 \vec{p}^2 + N^2 m^2 + \eta N^n E^n N^2 \vec{p}^2 / (N^n E_p^n) \simeq \vec{p}_{TOT}^2 + m_{TOT}^2 + \eta E_{TOT}^n \vec{p}_{TOT}^2 / (N^n E_p^n)$ .

still obtainable from the dispersion relation using  $v = dE/dp$ , as it happens to be the case in classical spacetime both in nonrelativistic (Galilei) physics and in relativistic (Einstein) physics. By assuming the validity of the relation  $v = dE/dp$  one is essentially only assuming<sup>3</sup> that it should be possible to introduce some form of Hamiltonian description of particle systems with standard Heisenberg commutator ( $[x, p] = 1$ ,  $v = dx/dt \sim [x, H]$ , where  $H$  is the energy/Hamiltonian). Combining (1) with  $v = dE/dp$  one is led to a velocity law which at “intermediate energies” ( $m < E \ll E_p$ ) takes the form

$$v \simeq 1 - \frac{m^2}{2E^2} + \eta \frac{n+1}{2} \frac{E^n}{E_p^n} . \quad (2)$$

Such a modified velocity law can be sensitively studied experimentally focusing on the fact that, whereas in ordinary special relativity two photons ( $m = 0$ ) emitted simultaneously would always reach simultaneously a far-away detector, according to (2) two simultaneously-emitted photons should reach the detector at different times if they carry different energy.

This type of effect can be significant[8, 9] in the analysis of short-duration gamma-ray bursts that reach us from cosmological distances. For a gamma-ray burst it is not uncommon to find a time travelled before reaching our Earth detectors of order  $T \sim 10^{17}s$ . Microbursts within a burst can have very short duration, as short as  $10^{-3}s$  (or even  $10^{-4}s$ ), and this means that the photons that compose such a microburst are all emitted at the same time, up to an uncertainty of  $10^{-3}s$ . Some of the photons in these bursts have energies that extend at least up to the  $GeV$  range. For two photons with energy difference of order  $\Delta E \sim 1GeV$  a speed difference  $\eta\Delta E/E_p$  over a time of travel of  $10^{17}s$  would lead to a difference in times of arrival of order  $\Delta t \sim \eta T \Delta E/E_p \sim 10^{-2}s$ , which is significant (the time-of-arrival differences would be larger than the time-of-emission differences within a single microburst).

Such a Planck-scale-induced time-of-arrival difference could be revealed[8, 9] upon comparison of the structure of the gamma-ray-burst signal in different energy channels. Considering the achievable sensitivities[39] one concludes that the next generation of gamma-ray telescopes, such as GLAST[39], can test very significantly (2) in the case  $n = 1$  (whereas the effects found in the case  $n = 2$  are too small for GLAST).

An even higher sensitivity to possible Planck-scale modifications of the velocity law could be achieved by exploiting the fact that, according to current models[40], gamma-ray bursters should also emit a substantial amount of high-energy neutrinos. Some neutrino observatories should soon observe neutrinos with energies between  $10^{14}$  and  $10^{19} eV$ , and one could, for example, compare the times of arrival of these neutrinos emitted by gamma-ray bursters to the corresponding times of arrival of low-energy photons. Assuming that some technical and conceptual challenges can be overcome<sup>4</sup> one could use this strategy to test very reliably the

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<sup>3</sup>Indeed most of the relevant phenomenological analyses assume the validity of  $v = dE/dp$ . But alternatives are being, legitimately, considered by some authors (see, *e.g.*, Refs. [35, 36, 37, 38]). While these studies of alternatives to  $v = dE/dp$  rely of a large variety of arguments (some more justifiable some less) in my own perception a key issue here is whether quantum gravity leads to a modified Heisenber uncertainty principle,  $[x, p] = 1 + F(p)$ , in which case the relation  $v = dx/dt \sim [x, H(p)]$  would not lead to  $v = dE/dp$ .

<sup>4</sup>For example, this type of analysis requires an understanding of gamma-ray bursters good enough to establish whether there are typical at-the-source time delays. The analysis would loose much of its potential if one cannot exclude some systematic tendency of gamma-ray bursters to emit high-energy neutrinos with,

case of (2) with  $n = 1$ , and even perhaps gain some access to the investigation of the case  $n = 2$ .

## 2.2 UHE cosmic rays

In alternative to the proposals considered in the previous subsection, in which one investigates the dispersion relation (1) in combination with the relation  $v = dE/dp$ , there has also been strong interest in the possibility of testing the implications of (1) when combined with the assumption of unmodified laws of energy-momentum conservation. With a given dispersion relation and a given rule for energy-momentum conservation one has a complete “kinematic scheme” for the analysis of particle production in collisions or decay processes. In the case in which one combines (1) with unmodified laws of energy-momentum conservation the analysis of course involves the added element of complexity due to the fact that one must necessarily introduce a preferred class of inertial frames<sup>5</sup>. The parameters (*e.g.* the parameter  $\eta$ ) will take different values in different inertial frames and therefore in order to combine meaningfully the limits obtained working in different frames it is necessary to transform all the results into limits applicable in a given inertial frame. It is customary to adopt as this “preferred” frame the natural frame for the description of the CMBR (Cosmic Microwave Background Radiation).

It has been observed that the combination of (1) with unmodified energy-momentum conservation can significantly affect the threshold requirements for certain particle-producing processes. Let us for example consider collisions between a soft photon of energy  $\epsilon$  and a high-energy photon of energy  $E$  that creates an electron-positron pair:  $\gamma\gamma \rightarrow e^+e^-$ . For given soft-photon energy  $\epsilon$ , the process is allowed only if  $E$  is greater than a certain threshold energy  $E_{th}$  which depends on  $\epsilon$  and  $m_e^2$ . For  $n = 1$ , combining (1) with unmodified energy-momentum conservation, this threshold energy  $E_{th}$  is found to satisfy

$$E_{th}\epsilon + \eta \frac{E_{th}^3}{8E_p} = m_e^2 \quad (3)$$

(assuming  $\epsilon \ll m_e \ll E_{th} \ll E_p$ ). The special-relativistic result  $E_{th} = m_e^2/\epsilon$  corresponds of course to the  $\eta \rightarrow 0$  limit of (3). For  $|\eta| \sim 1$  the Planck-scale correction can be safely neglected as long as  $\epsilon > (m_e^4/E_p)^{1/3}$ . But eventually, for sufficiently small values of  $\epsilon$  and correspondingly large values of  $E_{th}$ , the Planck-scale correction cannot be ignored. For  $\epsilon \sim 0.01eV$  the modification of the threshold is already significant, and this is relevant for the observation of multi-*TeV* photons from certain Blazars[12, 13].

And the process  $\gamma\gamma \rightarrow e^+e^-$  is not the only case in which this type of Planck-scale modification can be important. There has been strong interest[10, 12, 13, 14, 16, 17, 41]

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say, a certain delay with respect to microbursts of photons (although by combining several observations from gamma-ray bursters at different distances one could partly compensate for this possible systematic effect).

<sup>5</sup>It has been recently realized[31, 32] that a dispersion relation of the type of (1) can be adopted without necessarily renouncing to the equivalence of inertial frames, at the cost of a deformation of boost transformations (just like one can replace the Galileian  $m = p^2/2E$  with the special-relativistic  $m = \sqrt{(E^2 - c^2p^2)}/c^4$  without renouncing to the equivalence of inertial frames, at the cost of replacing Galilei boosts with Lorentz boosts). However, if one insists both on the equivalence of inertial frames and on a dispersion relation of type (1) the law of energy-momentum conservation cannot remain unmodified[31].

in “photopion production”,  $p\gamma \rightarrow p\pi$ , where again the combination of (1) with unmodified energy-momentum conservation leads to a modification of the minimum proton energy required by the process (for fixed photon energy). In the case in which the photon energy is the one typical of CMBR photons one finds that the threshold proton energy can be significantly shifted upward (for negative  $\eta$ ), and this in turn should affect at an observably large level the expected “GZK cutoff” for the observed cosmic-ray spectrum. Observations reported by the AGASA[42] cosmic-ray observatory provide some encouragement for the idea of such an upward shift of the GZK cutoff, but the issue must be further explored. Forthcoming cosmic-ray observatories, such as Auger[43], should be able[10, 13] to fully investigate this possibility.

### 3 Limitations of “cocktail analyses” in the search of quantum-gravity signatures in astrophysics

I stressed that it would be ideal to test directly (1), without the need of relying on any other assumption on properties of Planck-scale physics. This Quantum-Gravity Phenomenology is trying to provide some hints for the solution of the quantum-gravity problem and a test of (1) could be useful from this perspective. But if our phenomenology mixes (1) with other assumptions we will only test a certain “cocktail” of assumptions for quantum gravity, with an obvious decrease in the quality of the insight gained. As mentioned we are unable to test sensitively (1) on its own, but still we should give priority to tests which require the fewest and the simplest (most natural) assumptions in combination with (1). The assumption of  $v = dE/dp$ , considered in Subsection 2.1, and the assumption of unmodified energy-momentum conservation, considered in Subsection 2.2, are good examples of what could be a single extra assumption to combine with (1). Unfortunately in certain observational contexts which at first sight appear to provide a good chance for Planck-scale sensitivity one then finds out that a comprehensive phenomenological analysis requires a combination of several assumptions about the Planck-scale regime. Two examples which I consider in this section will illustrate the limitations that can emerge from relying on such cocktails of assumptions.

#### 3.1 Synchrotron radiation from the Crab nebula

A recent series of papers[44, 45, 46, 47, 48, 49, 50] has focused on the possibility to set limits on Planck-scale modified dispersion relations focusing on their implications for synchrotron radiation. By comparing the content of the first estimates<sup>6</sup> produced in this research line[44] with the understanding that emerged from follow-up studies[45, 46, 47, 48, 49, 50] one can gain valuable insight on the risks involved in analyses based on cocktails of several

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<sup>6</sup>Ref. [44] is at this point obsolete, since the relevant manuscript has been revised for the published version[46] and the recent Ref. [50] provides an even more detailed and careful analysis. It is nevertheless useful to consider this series of manuscripts [44, 46, 50] as an illustration of the inevitable increasing level of complexity of the analysis that emerges as more and more interplays within the system of assumptions are taken into account.

assumptions about Planck-scale physics. In Ref.[44] the starting point is the observation that in the conventional (Lorentz-invariant) description of synchrotron radiation one can estimate the characteristic energy  $E_c$  of the radiation through a heuristic analysis[51] leading to the formula

$$E_c \simeq \frac{1}{R \cdot \delta \cdot [v_\gamma - v_e]} , \quad (4)$$

where  $v_e$  is the speed of the electron,  $v_\gamma$  is the speed of the photon,  $\delta$  is an angle obtained from the opening angle between the direction of the electron and the direction of the emitted photon, and  $R$  is the radius of curvature of the trajectory of the electron. Ref. [44] implicitly relies on several assumptions[45, 47, 48, 49, 50], including: (i) the assumption that both the dispersion relation (1) and the relation  $v = dE/dp$  are verified; (ii) the assumption that the same heuristic derivation of the synchrotron-radiation cutoff energy applies exactly also at the Planck-scale, which in particular requires[45, 46, 48] that an ordinary effective low-energy field-theory description is possible; (iii) the assumption that the relation between the “opening angle”  $\delta$  and the energy  $E$  of the electron emitting the radiation is unaffected by the Planck-scale departures from Lorentz symmetry.

As an opportunity to test the corresponding modification of the value of the synchrotron-radiation cutoff one can hope to use some relevant data[44, 46] on photons detected from the Crab nebula. The observational information on synchrotron radiation being emitted by the Crab nebula is rather indirect: some of the photons we observe from the Crab nebula are attributed to synchrotron processes on the basis of a promising (but unconfirmed) conjecture, and the value of the relevant magnetic fields is also conjectured (not directly measured). But let me set aside these (however important) facts about the observational situation, since I here want to focus on the problems that arise when relying on “cocktails of assumptions” (independently of the reliability of the data which are being considered). The assumptions on which Ref. [44] relies clearly limit the insight gained through the phenomenological analysis.

Assuming that indeed the observational situation has been properly interpreted and relying on the additional assumptions (i), (ii) and (iii) one could basically rule out[44] the case  $n = 1$  for the modified dispersion relation (1). However, it was then realized[52] that the assumptions (i) and (ii) are not fully compatible: if one sets up dynamics according to the rules of effective low-energy field theory one cannot assume the dispersion relation (1) to apply to photons. At linear order in the Planck length ( $n = 1$ ) one can write terms that modify the dispersion relation for photons but the effect is then automatically such that it involves a strong helicity dependence: if right-circular polarized photons satisfy the dispersion relation  $E^2 \simeq p^2 + \zeta p^3$  then necessarily left-circular polarized photons satisfy the “opposite sign” dispersion relation  $E^2 \simeq p^2 - \zeta p^3$ . For spin-1/2 particles Ref. [52] does not appear to impose upon us a similar helicity dependence but of course in a context in which photons experience such a complete correlation of the effect with helicity it would be awkward to assume that instead for electrons the effect is completely helicity independent. One therefore introduces two independent parameters  $\eta_+$  and  $\eta_-$  to characterize the modification of the dispersion relation for electrons. In the more recent quantum-gravity analyses of synchrotron radiation from the Crab nebula[50] this realization has led to more prudent claims concerning the implications of these observations for the idea of modifications of the dispersion relations with terms linear in the Planck length ( $n = 1$ ): the analysis (as presently formulated) is

only relevant for quantum-gravity scenarios that are compatible with the type of needed low-energy effective field theory that is used in the analysis and in those contexts it can only be used to constrain one of the three parameters  $(\zeta, \eta_+, \eta_-)$  that would characterize the modification of the dispersion relation in a low-energy effective-field-theory setup.

I must stress that, while it is of course legitimate to develop a quantum-gravity-phenomenology test theory that is formulated in the effective-field-theory language, by adopting an effective-field-theory formalism one can anyway only provide rather limited insight for the overall effort of quantum-gravity research. In fact, a significant portion of the quantum-gravity community is justifiably skeptical about the insight gained from analyses relevant for the quantum-gravity problem done within low-energy effective field theory. In particular, the first natural prediction of low-energy effective field theory in the gravitational realm is a value of the energy density which is some 120 orders of magnitude greater<sup>7</sup> than allowed by observations. Somewhat related to this “cosmological constant problem” is the fact that a description of possible Planck-scale departures from Lorentz symmetry within effective field theory can only be developed with a rather strongly pragmatic attitude; in fact, while one can introduce Planck-scale suppressed effects at tree level, one of course expects<sup>8</sup> that loop corrections would naturally lead to inadmissibly large departures from ordinary Lorentz symmetry.

Perhaps most importantly, if we look at the quantum pictures of spacetime that provide support for the proposal (1), which usually involve either noncommutative geometry or Loop Quantum Gravity, at the present time one does not find any encouragement for this type of low-energy effective-field-theory description. The noncommutative spacetimes in which modifications of the dispersion relation are being most actively considered are characterized by spacetime-coordinate noncommutativity of the type  $[x_\mu, x_\nu] = i\theta_{\mu\nu} + i\rho_{\mu\nu}^\beta x_\beta$ , and it is well known that the construction of quantum field theories in these spacetimes requires the introduction of several new technical tools, which in turn lead to the emergence of several new physical features, even at low energies. When the matrix  $\rho$  is present ( $\rho \neq 0$ ) we are still struggling in the search of a satisfactory formulation of a quantum field theory[55, 56]. For the special case  $\rho = 0$  the community has achieved substantial progress in the development of quantum field theories[57], but the results actually show that it is not possible to rely on an ordinary effective low-energy quantum-field-theory description. In fact, one finds a surprising “IR/UV mixing”[29, 57, 58], *i.e.* the high-energy sector of the theory does not decouple from the low-energy sector, and this in turn affects very severely[58] the outlook of analyses based on an ordinary effective low-energy quantum-field-theory description. Indeed in the study reported in Ref. [59], which was announced soon after the first papers on the quantum-gravity implications of synchrotron radiation from the Crab nebula, a quantum field theory in noncommutative spacetime with modified dispersion relation was analyzed focusing on synchrotron radiation and it was argued that the limitations suggested by Ref. [44, 46] do

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<sup>7</sup>And the outlook of low-energy effective field theory in the gravitational realm does not improve much through the observation that exact supersymmetry could protect from the emergence of any energy density. In fact, Nature clearly does not have supersymmetry at least up to the TeV scale, and this would still lead to a natural prediction of the cosmological constant which is some 70 orders of magnitude too high.

<sup>8</sup>Indeed some studies, notably Refs. [53, 54], have shown mechanisms such that within an effective-field-theory approach loop effects would lead to inadmissibly large departures from ordinary Lorentz symmetry.



not actually apply.

The assumption of availability of an ordinary effective low-energy quantum-field-theory description finds also no support in Loop Quantum Gravity. Indeed, so far, in Loop Quantum Gravity all attempts to find a suitable limit of the theory which can be described in terms of a quantum-field-theory in background spacetime have failed. And on the basis of some recent studies[60] it appears plausible that in most contexts in which one would naively expect a low-energy field theory description Loop Quantum Gravity might predict a density-matrix description.

Also worrisome is the assumption that the relation between the opening angle  $\delta$  and the energy  $E$  of the electron emitting the radiation should be unaffected by the Planck-scale departures from Lorentz symmetry. It is in fact well established that assuming (1) in the analysis of particle-physics processes one naturally finds striking modifications of the formulas that relate the energy-momentum of the incoming particles with the opening angles between the directions of motion of the outgoing particles. For example, the result here discussed in Subsection 2.2, the modification of the threshold energy for  $\gamma + \gamma \rightarrow e^+ + e^-$ , can be viewed[45] as an effect due to a significant modification of an opening-angle formula.

This concern for the opening-angle estimate of Ref. [44, 46, 50] becomes even more serious considering the fact that synchrotron radiation can be described in terms of Compton scattering with the virtual photons of the magnetic field. Describing the virtual photon as a particle with momentum  $P_*$  and energy  $E_*$  one finds that in the process  $e^- + \gamma_{virtual} \rightarrow e^- + \gamma$  the opening angle  $\phi$  between the outgoing particles must satisfy the relation

$$\cos(\phi) \simeq \frac{2p_f E_{\gamma,out} - 2E_i E_* - 2p_i P_* - (E_*^2 - P_*^2) + \frac{E_{\gamma,out}}{E_f} m_e^2 + \frac{2\eta E_f^2 E_{\gamma,out}}{E_p}}{2p_f E_{\gamma,out}}, \quad (5)$$

where  $E_i$  ( $p_i$ ) is the energy (momentum) of the incoming electron,  $E_f$  is the energy of the outgoing electron, and  $E_{\gamma,out}$  is the energy of the (real, on-shell) photon that is emitted. For negative  $\eta$  the Planck-scale correction term can induce a significant reduction of the opening angle, which would affect<sup>9</sup> the analysis of Ref. [44, 46, 50].

## 3.2 Phase coherence of light from extragalactic sources and time quantization

The analysis of Ref. [61] can provide a second example of a physical context in which at first sight there appears to be a good chance for Planck-scale sensitivity but then it emerges that a comprehensive phenomenological analysis requires a combination of too many assumptions about the Planck-scale regime. The observations that are relevant for the analysis of Ref. [61] are the ones that provide evidence of a good phase coherence of light from extragalactic sources. And the key objective of the analysis reported in Ref. [61] is a test of the possibility

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<sup>9</sup>From private communications I infer that Jacobson, Liberati and Mattingly are not too concerned about this opening-angle issue (while they are making a dedicated effort of exploration[50] of the consistency requirements that emerge from the use of effective field theory in their analysis). They do comment briefly on this opening-angle issue in Ref. [47], but I must leave to the interested reader the task of assessing whether those brief comments do provide sufficient reassurance.

that time may be fuzzy/quantized at the Planck scale ( $\tau_p$  quantization, with  $\tau_p \sim 10^{-44}s$  the Planck time).

I should mention parenthetically that the analysis of Ref. [61] has been criticized at a merely computational level, especially for what concerns the way in which nonsistematic effects were combined[62] and the nature of the conventional-physics processes that lead to phase coherence of light from extragalactic sources[63]. Just like I set aside in the previous subsection the concerns for the nature of the data on synchrotron radiation from the Crab Nebula, here I want to set aside this type of skepticism toward the analysis reported in Ref. [61]. I intend to focus on the fact that in the phenomenological analysis presented in Ref. [61] the hypothesis of Planck-scale time quantization is not tested directly, but rather it is combined with a rich cocktail of assumptions, including: (j) that time quantization should be accompanied by a corresponding level of distance quantization, *i.e.* a combined measurement of space-position and time should be affected by  $\delta x > L_p$  and  $\delta t > \tau_p$  uncertainties, (jj) that a framework hosting these Planck-scale uncertainties in time and space-position should necessarily also predict irreducible uncertainties for energy and space-momentum measurement of the type  $\delta E > E^2/E_p$  and  $\delta p > p^2/E_p$ , and (jjj) that one should also necessarily have a modification of the dispersion relation roughly of the type (1).

While each of these conjectured features for quantum spacetime are individually plausible, it is rather “optimistic” to expect that all of them should be realized in the correct quantum-gravity theory. And actually some results in the literature show that there is no absolute link between the assumptions (j), (jj) and (jjj). Once again I can mention some results obtained in the study of spacetime noncommutativity of the type  $[x_\mu, x_\nu] = i\theta_{\mu\nu} + i\rho_{\mu\nu}^\beta x_\beta$ , which is one of the most popular and simplest ways to introduce spacetime quantization. A wide body of literature (see, *e.g.*, Refs. [29, 34, 56, 57, 64, 65, 66]) shows that in these quantized spacetimes energy and momentum, when properly introduced, are not affected by any minimum-uncertainty conditions, contrary to the assumption (jj).

Moreover, for the most popular choices of the matrices  $\theta$  and  $\rho$  the emerging spacetime quantization does not lead to the conclusion that a combined measurement of space-position and time should be affected by  $\delta x > L_p$  and  $\delta t > \tau_p$  uncertainties. For example the so-called  $\kappa$ -Minkowski spacetime is characterized by  $[x_j, x_l] = 0$ ,  $[x_j, t] = ix_j/\kappa$  (where  $\kappa$  is a noncommutativity scale with dimensions of mass) and is therefore fully compatible with the possibility of assigning sharp values to the space coordinates  $x_j$  (while indeed the time coordinate  $t$  is subject to a meaningful Planck-scale discretization[65]).

## 4 The Planck-boost regime

Together with a brief review and reanalysis of existing areas of interest in quantum-gravity phenomenology, I like to include in these notes also some remarks on a previously unnoticed opportunity which I see for this subject. I can do this while remaining in the context of the research line that investigates the fate of Lorentz symmetry in quantum spacetime, on which I mainly focused throughout these notes.

My point originates from the realization that some rather different “amplification mechanisms” are at work in the various processes I considered. For example, the threshold anomalies can get large when the two colliding particles have a large energy difference (one

is soft and one is very hard), *i.e.* when the laboratory frame is highly boosted with respect to the center-of-mass frame. The time-of-travel analyses, which I considered in discussing gamma-ray bursts, get larger at higher particle energy, and for a massive particle they are therefore more significant if the laboratory frame is highly boosted with respect to the rest frame of the particle.

My discussion was mainly focused on a specific model of Planck-scale departures from Lorentz symmetry, and it is clearly strongly model dependent (if the model is changed one can expect even sizeable changes in the nature and magnitude of the effects). But there is one aspect that might have more general, nearly model-independent, validity: the new Planck-scale effects become significant for high boosts with respect to the center-of-mass (or particle-rest) frame. Within a specific model a detailed analysis is needed in order to establish which type of high boosts are sufficient for a significant size of the effects. But it would be useful to have a more general intuition for a large-boost regime that is of interest from a quantum-gravity perspective. For example, in studies of the short-distance structure of spacetime different pictures lead to different expectations for the distance scale where the nonclassical features become relevant, but there is a distance scale which is perceived to be intrinsically of interest from a quantum-gravity perspective: when the processes involve distance scales of the order of the Planck length most researchers share the expectation that new effects should be present, quite independently of the specific models that different researchers are pursuing. For boosts we do not yet have a similar intuition. The Planck scale is interpreted equivalently as a length or energy scale, but there is no common expectation of a characteristic size of boosts that corresponds to the Planckian regime. To the idea of a large boost most researchers associate the image of particles with velocity “close to 1”, but no standard measure of “how close is close enough” has been adopted. Distance scales are small enough to be potentially sensitive to Planck-scale effects when they are of the order of the Planck length. Is there a model-independent way to describe a particle’s velocity as “high enough to be potentially sensitive to Planck-scale effects”?

It seems to me that the Planck length also allows to introduce an objective reference for the magnitude of boosts, at least in certain contexts. Take in particular a particle of rest energy  $m$ . By going from the rest frame to some boosted frames the same particle will carry a frame-dependent energy  $E$ , and the size of the energy of the particle measures the magnitude of the boost needed to connect the laboratory frame to the rest frame. In ordinary special relativity  $E/m = \cosh(\xi)$ , where  $\xi$  is the rapidity of the laboratory frame with respect to the rest frame. So energy can measure, in an appropriate sense, the magnitude of some relevant boosts. And I observe that the availability of the Planck scale allows to introduce two different regimes: the low-boost regime  $E/m < E_p/E$  and the high-boost regime  $E/m > E_p/E$ . In principle one can consider even a series of energy/boost values that get us deeper and deeper in the Planck regime:  $m < E < \sqrt{mE_p}$ ,  $\sqrt{mE_p} < E < (mE_p^2)^{1/3}$ ,  $(mE_p^2)^{1/3} < E < (mE_p^3)^{1/4}$ ,  $\dots$

The key point of this simple observation is that it suggests that, while normally one refers to the Planck regime as the regime of energies close to the Planck energy, there is a sense in which access to the Planck regime could be characterized as a requirement for a combination of particle energy, particle mass and Planck scale.

There is also a rather amusing quantitative observation that I can report on this point.

The standard estimate of the mentioned GZK scale for cosmic-ray observations is of order  $5 \cdot 10^{19} eV$ , which happens to be [67] just above the scale  $\sqrt{m_{proton} E_p} \sim 3 \cdot 10^{18} eV$  for a cosmic-ray proton. One could therefore suspect that the anomalies reported by the AGASA [42] observatory for the cosmic-ray spectrum (if at all to be trusted) might reflect some new physics in the high-boost/high-velocity regime  $E > \sqrt{m E_p}$ . Of course a minimum requirement for justifying interest in this numerological observation is confirmation by the mentioned forthcoming Auger data. But it is noteworthy that, in case it is needed, cosmic rays are not the only opportunity to access the high-boost regime. In fact, as mentioned, some neutrino observatories should soon observe neutrinos with energies between  $10^{14}$  and  $10^{19} eV$ , and although the precise values of the neutrino masses remain undetermined, on the basis of the present upper limits one can expect that these data will be sufficient to explore the high-boost regime for neutrinos (for example  $\sqrt{m E_p} < 10^{14} eV$  only requires that  $m < 1 eV$ ). By combining the information from observations of UHE cosmic rays and observations of UHE neutrinos we might gain in the near future some access to the Planck-boost regime.

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